

Enhanced Gamma Ray Signals in Cosmic Proton-Wimp Collisions Due to Hadronization

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In this paper, we investigate the gamma ray signal produced from dark matter collisions with high energy cosmic protons. Notably, we extend past results by including important hadronization effects. Showering and hadronization produces a high multiplicity of photons from the decays of hadrons, whose rate is not suppressed by the fine structure constant. Notably, proton remnants that do not participate in hard scattering, can produce a large rate of photons in the forward direction. These effects significantly enhance the photon rate and alter the energy and angular distributions compared to previous results which used only parton level calculations. Due to this modification, the gamma ray signal from the nearby active galactic nuclei Centaurus A is potentially testable in future Fermi-LAT and HESS measurements, for a dark matter mass and coupling consistent with current XENON100 bounds.

I. INTRODUCTION

The fundamental nature of dark matter remains mysterious to this day. The impressive consistency with the dark matter paradigm on a wide range of scales is tempered by the fact that only its universal gravitational interactions have been observed. To go further in our understanding, obtaining solid evidence of dark matter interactions with the Standard Model would be of enormous value. One promising approach to test such interactions is observing cosmic gamma rays. Dark matter can produce gamma rays through annihilation or decay and is currently being searched for by experiments such as Fermi-LAT [1] and HESS [2].

Another dark matter gamma ray signal that is less well known is gamma rays produced in collisions of dark matter with high energy cosmic particles. This indirect signal was proposed initially by Elliot and Wells [3] and has been reinvestigated more recently. Specifically, gamma rays from collisions between cosmic ray (CR) and dark matter (DM) particles have been studied in regions with concentrated dark matter and high energy cosmic ray flux, near the center of active galactic nuclei (AGN) [4, 5] and also the central region of the Milky Way [6]. Refs. [3–5] investigated the parton-level radiation and showed that the scattering between dark matter and the cosmic electrons in AGNs can be a promising gamma ray signal. On the other hand, [4] found that proton-wimp interactions lead to a less promising signal due to the quark’s fractional charge and momentum distribution in the proton. However, this analysis was a parton-only calculation and neglects important effects, such as showering and hadronization. In this study, we demonstrate that the hadronic shower contributes a large number of photons from hadron decays. Notably, this photon production is enhanced relative to the parton-only calculation due to large multiplicity and the lack of suppression by α_{QED} . Furthermore, these photons have a substantially altered energy spectra, with energies extending to higher values compared to those from the hard scattering process. The hard scattering occurs at an energy scale related to the dark matter mass, which can be much lower than the total incoming proton energy. The showering from the rest of the proton, which does not participate in the hard scattering and is likely to carry the majority of the incoming energy, can emit very energetic photons in the forward direction. For AGNs, this enhancement allows the small fraction of protons directed towards the Earth to give a significant gamma ray contribution. To summarize, we find that the photons of the shower are an important modification to the gamma ray signal from proton-dark matter scattering which greatly enhances the rate and modifies the shape of the energy spectrum.

In our analysis we adopt a toy model of a Majorana fermion dark matter, that couples to the right-handed up quark through a heavy charged scalar. This simple model serves as a template for models where the dark matter - cosmic ray collisions give an important photon signal, while other signals, like dark matter annihilation, become suppressed. With a heavy partner to a standard model quark, the collision process can undergo an s-channel resonance, leading to a large scattering cross-section. This can be consistent with bounds from direct detection experiments where the \sim keV recoil energy is much lower than the resonance energy. Interestingly, as most of the photon radiation is emitted on resonance, the photon spectral structure is determined by the mass difference between the DM and the heavy p/e^- partner, instead of the mass of DM itself. This creates freedom in the signal’s energy scale that differs from that from DM annihilation and decay cases.

The rest of this paper is organized as follows. In Section II we discuss the resonant scattering process in the toy model. We take into account the allowed mass range from the latest XENON100 constraints [8], to determine allowed signal benchmarks. Section III outlines the calculation of the gamma ray spectrum. In Section IV we study the signal from collisions off cosmic rays for the AGN Centaurus A. In Section V we comment on the enhancement on the gamma rays from dark matter collisions with diffuse cosmic rays. A summary is presented in Section VI. Finally, in the Appendix A, we list some important formulas for diffuse cosmic ray scattering.

II. RESONANT COSMIC RAY-DARK MATTER SCATTERING

The rates of cosmic ray-dark matter scattering production of gamma rays are particularly interesting when there is an s-channel resonance enhancement [4]. For example, a heavy scalar partner to the up quark, ϕ , can mediate an s-channel resonance as shown in the left column of Fig.1. This should be compared with the three processes in the right column which illustrate the leading parton-level photon emission.

In the galaxy, the dark matter χ is non-relativistic. Thus, the condition on the up-quark’s energy to hit the resonance is (neglecting the up quark mass)

$$M_\phi^2 = s = (p_\chi + p_u)^2 = M_\chi^2 + 2E_u M_\chi \quad \text{or} \quad E_u = E_{res} \equiv \frac{M_\phi^2 - M_\chi^2}{2M_\chi} \quad (1)$$

where s is the square of the center-of-mass (COM) frame energy. To realize this signal, we will consider a theory with

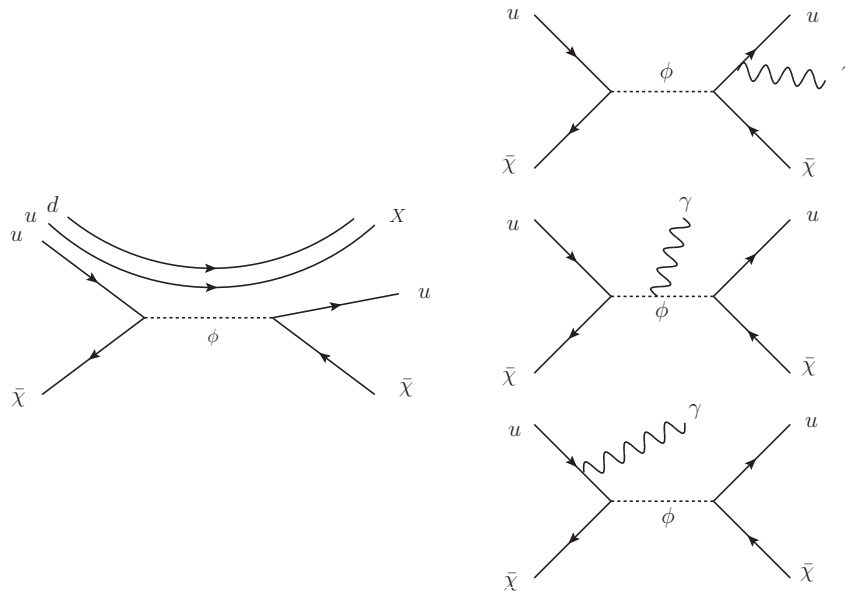


FIG. 1. Resonant s-channel diagrams. The charged u -partner, ϕ , can also radiate photons. The left panel is the leading 2 to 2 collision and the right panel shows the leading $\chi u \rightarrow \chi u \gamma$ processes that dominates the hard event's photon emissions.

a Majorana fermion dark matter with the interaction,

$$\mathcal{L}_{int} = y \bar{\chi} P_R u \phi^* + h.c. \quad (2)$$

where the dark matter χ only couples right-handedly to the up quark via the scalar ϕ , a colored partner to the up quark that carries the same electric charge. We choose the dark matter to be Majorana to avoid inducing large spin-independent scattering which would be strongly excluded by direct detection experiments. Furthermore, the right-handed coupling ensures that non-relativistic annihilation $\chi\chi \rightarrow u\bar{u}$ is chirality suppressed. For proton energies above E_{res} , integrating out the parton distribution function (PDF) always ensures hitting the s-channel resonance. Due to the enhancement at the resonance, the total high energy scattering cross-section increases as $\sim y^2$. As we will show, the direct detection bounds are more stringent at larger coupling, which can be avoided by taking a larger mass gap between χ and ϕ . However, since this mass gap also determines the gamma ray spectra, there is a complicated interplay between satisfying direct detection limits and enhancing the gamma ray signal. Thus, to be concrete, we set $y = 1$ throughout this paper and will choose the mass gap to be consistent with direct detection limits.

The ϕ decay width is

$$\Gamma_\phi = \frac{y^2}{16\pi} M_\phi \left(1 - \frac{M_\chi^2}{M_\phi^2}\right)^2 \quad (3)$$

which is less than $\mathcal{O}(10^{-2} M_\phi)$ in our analysis. For such a narrow width, the s-channel resonance dominates when kinematically allowed and the total $\sigma_{\chi p}$ shoots up for $E_p > E_{res}$. While $\sigma_{\chi p}$ continues to grow with proton energy, the cosmic proton flux normally decreases as a power-law spectrum. Thus the total gamma ray signal depends on the energy where $\sigma_{\chi p}$ turns up, which is determined by the mass gap between χ, ϕ .

This mass gap has a lower bound from direct detection experiments since the scattering rate is enhanced in the squeezed limit [7]. In Fig. 2, we show the minimal mass differences allowed by recent XENON100 results [8] at 90% confidence level. We have included the spin-dependent (SD) scattering and also the spin-independent (SI) scattering induced by the twist-2 operator [9], which are comparable in importance near the bound. Due to the resultant change in the energy spectrum, we cannot use XENON100's limit which is based on a profile likelihood. To construct our own limit, we use XENON100's hard discrimination cut acceptance shown in their Fig. 1 [8] and require less than 5.3 expected signal events, which is the 90% CL limit given their two observed events. As a cross check, our derived limit on the SI cross section $\sigma_{\chi N}$ is slightly weaker than their observed profile likelihood limit, but consistent within the 1σ expected sensitivity band in their Fig. 3 [8]. We refer to [7, 10] for further details of the SD and SI cross section calculations.

As two benchmarks, we use points A and B at $(m_\chi, m_\phi) = (300, 405)$ GeV and $(1, 1.04)$ TeV, While a narrower mass gap can be allowed for a lower y , the scattering cross-section decreases faster than the gain from a lower resonance CR energy (for the assumed E^{-2} spectrum in this paper). Thus the gamma ray signal turns out to be less favorable with smaller couplings. At the sample points, non-relativistic annihilation $\chi\chi \rightarrow u\bar{u}$ is chirality suppressed by the small u-quark mass. The leading annihilation process is $\chi\chi \rightarrow u\bar{u}g$, with a sub-picobarn $\langle v\sigma \rangle$ that is allowed by PAMELA [11] results on the local \bar{p}/p ratio.

Although a light dark matter at multi-GeV mass may evade the direct detection bounds [12], in our SUSY-inspired toy model the charged scalar partner ϕ is required to have a very small mass difference from the dark matter candidate, in order avoid detection at LEP and LHC. While such a scenario is possible, it is beyond the scope of this paper to fully study the collider bound at a narrow corner of our toy model.

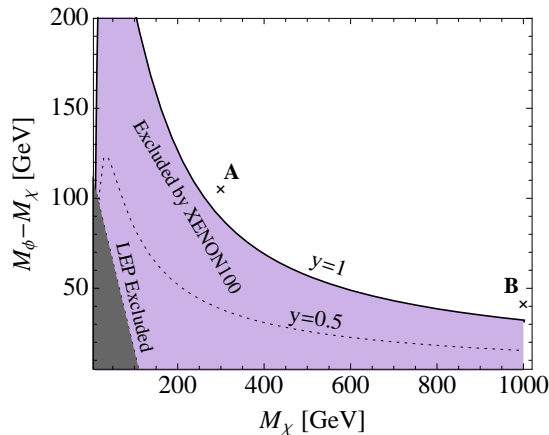


FIG. 2. Dark matter and u-partner masses allowed by 2012 XENON100 results at 90% C.L. Sample mass points are marked above the $y = 1$ bound. The XENON100 constraint with $y = 0.5$ (dotted) is also shown as the dotted curve for comparison.

III. PROMPT GAMMA SPECTRUM

When cosmic rays collide off dark matter, photons are emitted either directly from the hard scattering process or produced during the shower. The parton level spectrum has been studied in detail in Ref. [4]. The high energy photons are emitted in different ways during χ, e^- and χ, p collisions, as described below.

In the case of χ, e^- collision, the leading photon emission is through the $\chi e^- \rightarrow \chi e^- \gamma$ process. When the electrons energy is above E_{res} , the initial state radiation (ISR) diagram takes over, with a hard ISR photon in the collinear direction that puts both the internal e^- and ϕ propagators on resonance (under the approximation where the electron is massless). However, the total cross-section is suppressed at large incoming electron energy, where $\sigma \sim E_e^{-1}$. As a result, the integrated photon spectrum over a power-law spectrum for incoming CR electrons falls sharply for $E_\gamma > M_\phi - M_\chi$.

For the case of wimp-proton collisions, the up quark's PDF in the proton takes the role of reducing the center-of-mass frame energy between the parton and dark matter without the necessity of extra radiation. This lifts the E_{CR} suppression on scattering cross-section at large proton energy. Final state photons originate in the hadronic showers around the scattered quark, but more importantly, from the proton remnants that carry off most of the incoming energy. However, the PDF preference on relatively low parton momentum fraction suppresses $\sigma_{\chi p}$ for $E_p \sim E_{res}$ and below. The $\sigma_{\chi p}$ shows a steep up-turn near E_{res} and continues to increase with E_p , which can be seen in the left panel of Fig. 5. Thus there is a larger contribution of high energy photons compared to the case of dark matter scattering off electrons.

The prompt photons in χ, p collision fall into two major categories:

1. Final state radiation (non-remnant FSR). Photons emitted by the hard-scattered u-quark and its shower belong to this category. As the proton PDF ensures the s-channel ϕ resonance, the final state (non-remnant) energy add up to the ϕ mass, and the FSR photons typically has energy below $\delta M = M_\phi - M_\chi$. However, since ϕ and χ are comparable in mass, the resonance $u - \chi$ system has small boost and the FSR photons can point at any direction and dominate the gamma ray signal at large scattering angles. The shower photons, resulting from hadron decays inside the hadronized jet, have in addition an enhancement due to large multiplicity and the lack

of suppression by the QED fine structure constant.

2. Shower from proton remnants. Similar to the ISR photon in χ, e^- collisions, at $E_{CR} > E_{res}$ the remnants are emitted along the proton's incoming direction. These photons can be emitted at energy much higher than $M_\phi - M_\chi$ but are mainly confined in this forward region. Notably, the number of the photons emitted in proton collisions exceed that in χ, e^- ISR. At lower incoming energy $E_{CR} \sim E_{res}$ or less, the collision does not hit resonance. Here, we find that the photons from remnants also are less energetic than $M_\phi - M_\chi$ but have greater freedom in their direction.

We calculated the photon spectrum from χ, p collisions with the Monte Carlo generator *Sherpa* [13], and its *Amegic* [14] and *Photons* [15] packages for showering and photon radiation. The dark matter Lagrangian is implemented with the *FeynRules* [16] package.

We use the hadronization model included in *Ahadic* [17] as implemented in *Sherpa*. It is designed to allow the study of deep-inelastic scattering (DIS) processes¹[18]. The resulting partons of our DIS-like hard process, $p\chi \rightarrow \chi + X$, and the proton remnants are first showered and then transformed into primordial hadrons during the cluster hadronization process. The subsequent decays of unstable hadrons are also handled by *Sherpa*. In fact, most of the photons produced in the simulation emerge from the decay of neutral mesons, such as π^0 or through final state radiation in hadron decays. Admittedly, the modeling for remnants is not experimentally tested for proton collisions with an neutral exotic particle. Thus, we warn that the theoretical uncertainties on the photon production can be large, especially in the forward region.

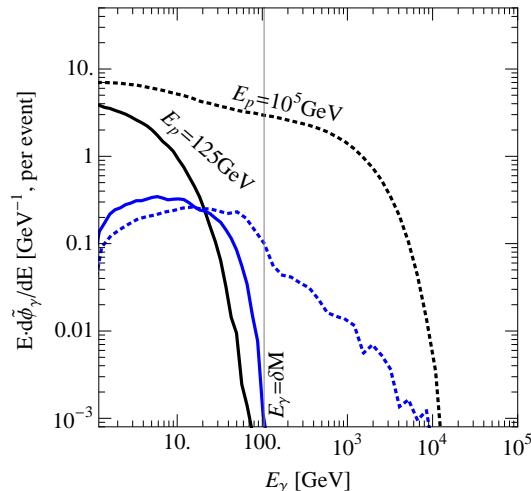


FIG. 3. Photon $E \frac{d\phi}{dE}$ spectrum at a near-threshold (125 GeV, solid) and high (10^5 GeV, dashed) proton energy. The spectra for parton level $\chi u \rightarrow \chi u \gamma$ are shown in blue color, where $\frac{d\phi}{dE}$ is normalized to one photon in each collision. Black curves are for fully showered $\chi p \rightarrow \chi X$ with remnants and have more photons per event. For all spectra, the dark matter mass is 300 GeV and the up quark partner is at 405 GeV.

Fig. 3 shows the photon spectrum from one χ, p collision event, comparing the fully showered $\chi u \rightarrow \chi u$ case with the hard photon spectrum from a parton level calculation of $\chi u \rightarrow \chi u \gamma$. For the parton level $\chi u \rightarrow \chi u \gamma$ calculation we imposed these cuts: photon $E, P_T > 1$ GeV and the invariant mass between u, γ greater than 1 GeV. Since the photon bremsstrahlung has a logarithmic dependence on the charged particle (u-quark) mass, these cuts may cause a factor of order $\mathcal{O}(1)$ to the normalization of parton level radiation, and do not qualitatively impact the results. Here we assume an isotropic distribution of incoming protons, at 125 GeV that is close to E_{res} (solid curves). This produces photons mostly below the mass gap $M_\phi - M_\chi$. This should be contrasted with the high energy case of $E_p = 10^5$ GeV (dashed curves). Note that the gap between the fully showered and parton level spectra widens for higher energy incoming protons, due to extra hard photons from remnants. For E_p above resonance energy, while the FSR photons remain below $M_\phi - M_\chi$, ISR and proton remnants photons continue to higher energies.

¹ We thank Stefan Hoeche for enabling Wimps as initial-state particles in the event generation in *Sherpa*.

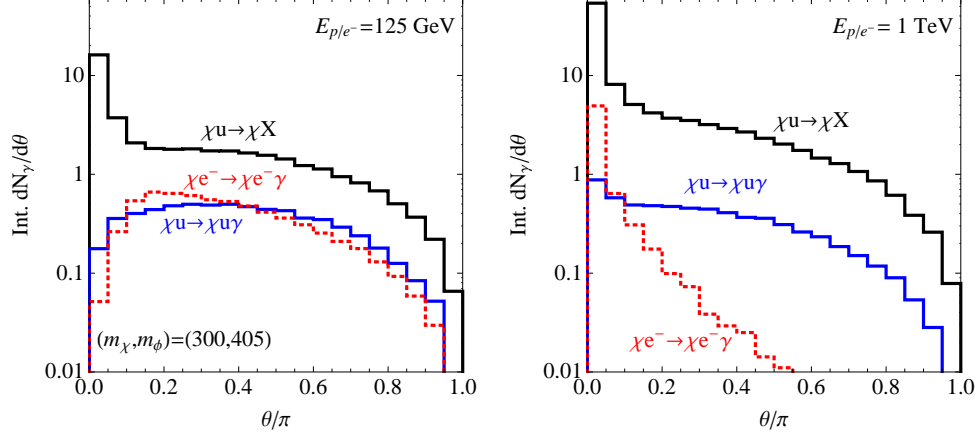


FIG. 4. Angular distribution of photons with $E_\gamma > 1$ GeV at cosmic ray energy near (left panel) and above (right panel) the resonance energy. θ denotes the photon's scattering angle off the incoming proton direction. Showered spectra are normalized to the number of final state photons, \tilde{N}_γ (above 1 GeV). Parton level curves are normalized to one photon per event and their gap to the fully showered curve at large scattering angle is due to \tilde{N}_γ . Note that above E_{res} the ISR dominates the $\chi e^- \rightarrow \chi e^- \gamma$ spectrum and emission at large angle diminishes. Furthermore, the behavior at small θ show how proton remnants provide extra forward photons. For incoming particles near resonance energy (left), photons from hard event are less peaked in the forward direction. The χe^- collision results are also shown for comparison. For all spectra, the dark matter mass is 300 GeV and the up quark (electron) partner is at 405 GeV. The parton level spectra have kinematic cuts that require both photon P_T and $u/e^-, \gamma$ invariant mass above 1 GeV.

In Fig. 4, we show the distribution of photons ($E_\gamma > 1$ GeV) over the scattering angle. Here the scattering angle θ is between the photon and the incoming proton's direction. Note that the remnants give a more pronounced peak in the forward direction for χ, p collisions, as exemplified by the 1 TeV incoming proton. Although χe^- collisions for high incoming electron energy also favors a forward ISR photon, the distribution of χ, e^- signal is dominated by $\sigma_{\chi e^-}$ near E_{res} , as seen in left panel of Fig. 5.

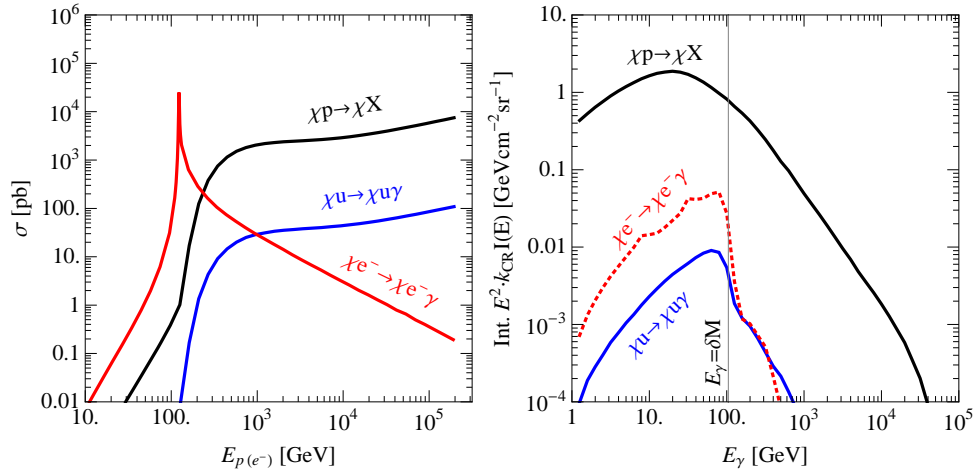


FIG. 5. (left:) Dark matter - cosmic p/e^- scattering cross-sections. The parton-level $\chi u \rightarrow \chi u \gamma$ cross-section depends on the kinematic cut on the final state photon, besides a generic α_{QED} suppression in comparison to that of the leading order $\chi u \rightarrow \chi u$. (right:) Unit-volume gamma ray spectra from full proton shower, parton level $\chi u \rightarrow \chi u \gamma$ and $\chi e^- \rightarrow \chi e^- \gamma$. In the right panel, the integrated flux $I(E_\gamma)$ is given in Eq. A5 with a reference energy $E_0 = 10$ GeV. The CR flux is taken as Eq. 12 with normalizations $k_p = 1$ and $k_{e^-} = 0.01$. In both panels the $\sigma_{\chi e^-}$ is scaled up by a factor of ~ 3 to compensate for the kinematic cuts. For all spectra, the dark matter mass is 300 GeV and the up quark (electron) partner is at 405 GeV.

The cross-sections for χ, p scattering are shown in Fig. 5. Scattering with an electron is also plotted as a comparison

for the high energy behavior of the cross section. The $\chi(u/e^-) \rightarrow \chi(u/e^-)\gamma$ processes use the same set of cuts as in Fig. 3. In the right panel of Fig. 5, the photon spectra from dark matter collisions with galactic cosmic rays is generated by convolving with a $E^{-2.7}$ proton spectrum (E^{-3} for e^-) that is typical for the cosmic rays in the central region of our Galaxy. The normalization on the electron flux is 10^{-2} of that of protons; see Appendix A for the definition of $I(E)$. Due to the lack of peaking near E_{res} , χ, p^- scattering yields a harder gamma ray signal above $M_\phi - M_\chi$. Compared to the parton level $\chi u \rightarrow \chi u \gamma$ prediction, we see that the showers give a roughly two order of magnitude enhancement in photons for proton-dark matter scattering. As previously mentioned, this difference is due to the α_{QED} suppression of the parton level cross section and a higher final state photon multiplicity \tilde{N}_γ from full hadronization/showering.

IV. THE AGN CASE: CENTAURUS A

An interesting place to look for χp collision is at the center of nearby AGNs, where dark matter halo is assumed to exist and luminous jets provide high energy protons. We take Centaurus A for our calculations. Although the proton composition of the AGN jet has large modeling uncertainty, protons can make up a majority of jet particles and the energy output in protons, L_p , from Cen. A can be more than 10 times higher than in leptons [1]. In this section, we compute the gamma ray signal arising from proton-dark matter collisions, with a focus on the contribution from proton remnants.

We make an assumption that protons are isotropic in the AGN's 'blob' frame, similar to the jet electrons. The spectrum of protons are not well known. We assume that the protons also undergo Fermi acceleration and their isotropic spectrum in the 'blob' frame is a power-law E^{-s} , where the index $s = 2$:

$$\frac{d\dot{N}_p}{d\tilde{E}d\tilde{\Omega}} = \frac{K_p}{4\pi} \left(\frac{\tilde{E}}{E_0} \right)^{-s} \quad (4)$$

The tilde $\tilde{}$ denotes variables in the boosted 'blob' frame. K_p is the normalization that is determined by AGN's proton output. The 'blob' frame moves at a Lorentz boost factor Γ_B relative to the central black hole. Following the analyses in [4, 5], we take $\Gamma_B = 3$. Boosting back to the black hole frame where the wimps are non-relativistic, the proton spectrum is

$$\frac{d\dot{N}_p}{dEd\Omega} = \frac{d\dot{N}_p}{d\tilde{E}d\tilde{\Omega}} \cdot \frac{1}{\Gamma_B(1 - \beta_B \cos \theta)} \quad (5)$$

where the $\beta_B = 0.94$ is the 'blob' frame's velocity. The energy and zenith angle before/after the boost are related by

$$\cos \tilde{\theta} = \frac{\cos \theta - \beta_B}{1 - \beta_B \cos \theta} \quad \tilde{E} = E \cdot \Gamma_B(1 - \beta_B \cos \theta). \quad (6)$$

with $\theta = 0$ along the jet axis. Combining Eq. 5 and 6, the black-hole frame proton spectrum is

$$\frac{1}{2\pi} \frac{d\dot{N}_p}{dE d\cos \theta} = \frac{K_p}{4\pi} \left(\frac{E}{E_0} \right)^{-s} \cdot [\Gamma_B (1 - \beta_B \cos \theta)]^{-(s+1)}, \quad (7)$$

which is still a power-law and has the same index as that in the 'blob' frame, while its intensity now varies with direction. For relativistic particles, the reference energy E_0 is irrelevant and can be absorbed into the normalization. Keeping a nonzero mass leads to a $\mathcal{O}(\gamma_p^{-2})$ correction to the formulae above, where $\gamma_p = E/m_p$. Integrating Eq. 7 with proton energy gives the total proton energy output as

$$L_p = K_p \cdot \frac{E_0^s}{2s(2-s)\beta_B\Gamma_B^{s+1}} (E_{max}^{2-s} - E_{min}^{2-s}) [(1 - \beta_B)^{-s} - (1 + \beta_B)^{-s}], \quad (8)$$

$$\text{or } K_p = \frac{L_p}{E_0^2 \Gamma_B \ln(E_{max}/E_{min})}, \text{ for } s = 2. \quad (9)$$

As Eq. 7 shows, while the flux along the jet direction is greatly enhanced, the Jacobian suppression at large angles $\propto \Gamma_B^{-3}$. The Cen. A jet is 68° ($\cos \theta = 0.37$) from the Earth; in this direction, the Jacobian from the Lorentz boost suppresses the proton flux by a factor of 0.14 compared to the unboosted flux. Most protons are along the jet axis, thus their gamma ray contribution towards the Earth is through large angle scattering. In terms of phase-space, for these 'along-axis' protons, a 4π integration of the Jacobian $\int |J| d\Omega$ is of order $\mathcal{O}(10^2)$ times favored by the Lorentz boost,

in comparison to the Jacobian integrated around an angular window $\Delta \cos \theta < 0.1$ centered on the protons pointed towards the Earth. Given the significant enhancement from proton remnants, the $\mathcal{O}(10 - 10^2)$ higher photon flux can negate/overcome this suppression at large incoming proton energy. While the low E_γ spectrum is still dominated by radiation from the protons along the jet axis, protons that point near to the Earth also make considerable contribution to the gamma ray signal, especially when $E_\gamma > M_\phi - M_\chi$.

Admittedly the Lorentz boosted ‘blob frame’ is a simplistic picture for the protons inside the AGN jet. If the AGN jet is more collimated than our assumption, less protons would point towards the Earth and the photons in the forward region would play a less important role. To illustrate this uncertainty in the AGN proton distribution, our signal prediction will also be shown with just the ‘along-axis’ protons with $\cos \theta_p > 0.8$.

Including radiation from protons in all directions, the photon flux towards Earth is

$$\left. \frac{d\phi_\gamma}{dE_\gamma d\Omega} \right|_{\vec{\theta}_\oplus} = \frac{1}{R^2} \frac{\delta_{DM}}{M_\chi} \int d\Omega_p \int dE_p \sigma(E_p) \frac{dN_p}{dE_p d\Omega_p} \left. \frac{d\tilde{N}_\gamma}{dE_\gamma d\Omega_{\gamma,sc}} \right|_{\theta_{\gamma,sc} = \angle \vec{\theta}_p, \vec{\theta}_\oplus}. \quad (10)$$

Throughout this paper we denote angular-integrated cosmic ray flux as ϕ and its angular differential form as $d\phi/d\Omega$. The direction of the incoming proton $\vec{\theta}_p = \{\theta_p, \phi_p\}$ is not limited to the vicinity of the jet axis. $\theta_{\gamma,sc}$ denotes the ‘real’ photon scattering angle in a frame where the proton momentum is along the z -axis. $\theta_{\gamma,sc}$ is determined by the proton direction $\vec{\theta}_p$ and the Earth’s direction $\vec{\theta}_\oplus$. $R = 3.7$ Mpc is the Earth’s distance to Cen. A. The integrand in Eq. 10 determines the contribution from protons at angle θ_p off the AGN jet axis. $\delta_{DM} = \langle \rho_\chi(r) \cdot r \rangle$ is the dark matter halo density integrated over the distance range where collisions occur; δ_{DM} at Cen. A can be as high as $10^{11} M_\odot/\text{pc}^2$ [4]. For the jet output in protons, we use $L_p = 1 \times 10^{45} \text{ erg s}^{-1}$ and an energy range $[E_{min}, E_{max}] = [10, 10^7] \text{ GeV}$ [1]. $\frac{d\tilde{N}}{dE_\gamma d\Omega_{\gamma,sc}}$ denotes the final state photon distribution from an average collision event. $\frac{d\tilde{N}}{dE_\gamma d\Omega_{\gamma,sc}}$ is normalized to the total number of photons above 1 GeV per collision and is Monte Carlo generated.

As shown in Fig. 6, the protons along the jet axis ($\cos \theta_p \sim 1$) suffices for parton level radiation (shown in blue dotted contours). The showered spectra (shown in black solid contours) shows that the forward photons, with $\cos \theta_p \sim 0.37$, mostly from proton remnants, account for a significant portion or even the majority of the signal, especially at large E_γ . Even at low E_γ , contributions from protons along the jet axis are still significant. The resulting gamma ray

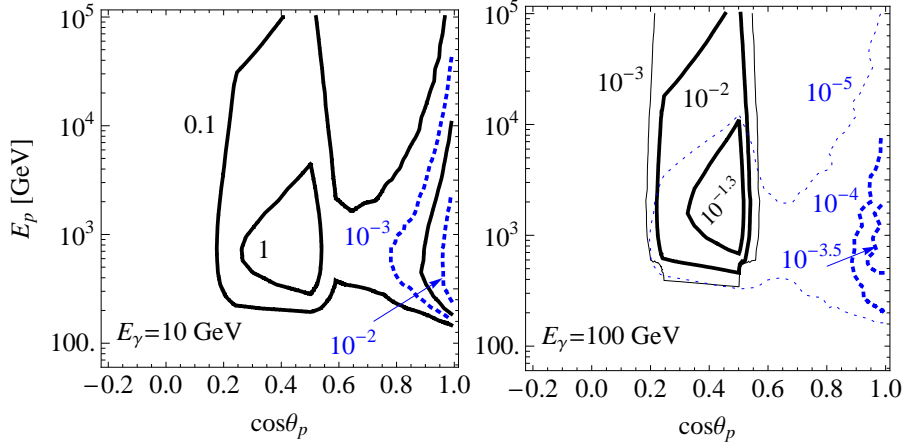


FIG. 6. Emission intensity contours in terms of proton energy and proton’s angle off the jet axis. Black and blue contours denote the showered (solid) and parton level (dotted) calculations, respectively. The azimuthal angle $\phi_p = 0$ in both panels, i.e. protons are in the Earth - jet axis plane. The Earth’s direction is $\cos \theta_p = 0.37$. Emission intensity f is the integrand in Eq. 10, in units of $\text{pb} \cdot \text{GeV}^{-2} \cdot \text{sr}^{-2} \cdot K_p|_{E_0=10 \text{ GeV}}$. For all spectra, the dark matter mass is 300 GeV and the up quark partner is at 405 GeV.

signal at the Earth is plotted in Fig. 7 in black. The signal is noticeably enhanced over the parton-level calculation shown in blue. Furthermore, the shape is substantially altered. At low energies, $E_\gamma < M_\phi - M_\chi$, the spectra is softer than the parton-level result and has less of a peaking structure. At high energies, $E_\gamma > M_\phi - M_\chi$, the fully showered spectrum is a power law at high energy which receives a significant contribution from protons along the jet axis. In comparison, the parton level photons drop abruptly after reaching $M_\phi - M_\chi$. Thus, taking into hadronization and showering has both significantly enhanced the signal and altered its spectral shape. Note that due to numeric stability issues in Monte Carlo, we do not plot E_γ above 1 TeV, yet the E^{-2} power-law spectrum is expected to extend to higher energy, as a fragmentation from the the total incoming proton energy.

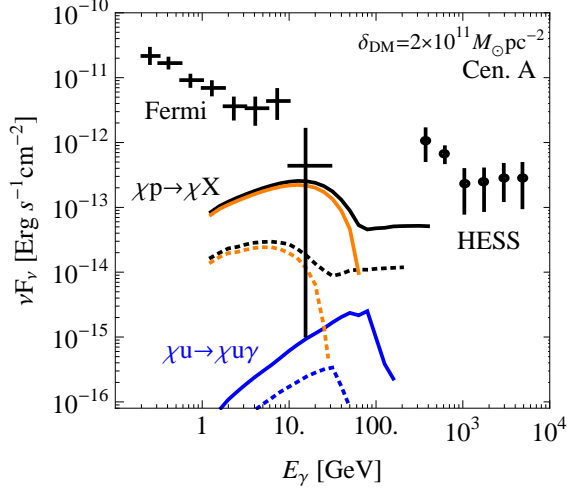


FIG. 7. χ, p collision induced gamma ray signal from Cen. A, for sample point A (solid) and B (dotted). The full collision and parton level $E^2 \frac{d\phi}{dE}$ spectra are plotted in black and blue colors, respectively. The orange curves show the component of the fully showered spectra that originate from protons along the AGN jet axis, $\cos \theta_p > 0.8$. Signal levels assume optimistic AGN parameters: $L_p = 10^{45} \text{ erg s}^{-1}$ and $\delta_{DM} = 2 \times 10^{11} M_{\odot} \text{ pc}^{-2}$ [4]. Fermi [1] and HESS [2] measurements are shown for comparison.

In Fig. 7, we have also plotted the signal component from the protons that are just along the AGN jet axis (shown in orange), integrating over $\cos \theta_p > 0.8$ in Eq. 10. This demonstrates the situation for a more highly collimated AGN jet, where only large-angle scattering gamma rays contribute. Thus, the high energy tail above $M_{\phi} - M_{\chi}$ is sensitive to the theoretical uncertainties of the AGN jet angular distribution as well as the photon contribution from proton remnants. As these curves show, for large angle scattering, the major difference is that such photons drop much more abruptly when E_{γ} approaches to $M_{\phi} - M_{\chi}$. The parton-level curves, while their normalizations are suppressed by $\alpha_{QED}/\tilde{N}_{\gamma}$, also demonstrate this high energy behavior of photons from hard scattering.

The overall signal level scales linearly with δ_{DM} and the AGN's energy output in protons. In illustrating the gamma ray signal we assumed an optimistic scenario with regards to the values of the dark matter density, the AGN's proton energy output and the interaction coupling. The resulting gamma ray signal level for sample point A is comparable to the uncertainties in the Fermi data and future observation may constrain the coupling to lower values. More optimistically, with further enhancements to the dark matter signal, the high energy tail could explain the HESS data points without modifying the lower energy Fermi points and thus resolve the discrepancy in power law observed by the HESS and Fermi-LAT analyses [1].

V. DIFFUSE PROTONS

For an isotropic distribution of protons, e.g. the diffuse protons inside the Milky Way, there is no preferred direction and the contribution from proton remnants are present in the 4π -averaged prompt spectrum. However, due to relatively low CR flux inside the Milky Way plus a high energy threshold for resonance scattering, the gamma ray signal is much below galactic background levels. In this section we only describe the calculations with two template profiles of galactic protons.

The photon signal is given by,

$$\frac{d\phi_{\gamma}}{dE_{\gamma}} = \int dr \frac{\rho_{\chi}(r)}{M_{\chi}} \int_{E_{\gamma}}^{+\infty} dE_p \sigma_{\chi p} \frac{d\phi_p}{dE_p} \frac{d\tilde{N}}{dE_{\gamma}} \quad (11)$$

where $\rho(\mathbf{r})$ is the dark matter halo density, $\frac{d\phi_p}{dE_p}$ is the cosmic ray flux. At the center of the Milky Way galaxy, these fluxes can be parametrized [19] as

$$\begin{aligned} \frac{d\phi_p}{dE_p d\Omega} &= k_p \left(\frac{E_p}{\text{GeV}} \right)^{-2.7} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} && \text{for protons} \\ \frac{d\phi_{e^-}}{dE_{e^-} d\Omega} &= k_{e^-} \left(\frac{E_{e^-}}{\text{GeV}} \right)^{-3} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} && \text{for electrons} \end{aligned} \quad (12)$$

Note: the flux normalizations k_{p/e^-} in lower-case are not to be confused with that of the AGN jet. Since the diffuse spectrum is isotropic, the forward photons are readily present and their spectrum is illustrated in Fig. 3.

For protons, its power law index only varies slightly during propagation and the spatial and energy parts in Eq. 11 can be separated,

$$\frac{d\phi_\gamma}{dE_\gamma d\Omega}(\theta) = J(\theta) \cdot I(E_\gamma) \quad (13)$$

where $J(\theta)$ integrates over the dark matter distribution along the direction θ , while $I(E_\gamma)$ is the prompt gamma spectrum convoluted with the proton energy spectrum. For details see Appendix A.

CR model	α_p	$M_\chi \cdot \bar{J}(\theta)$ Central	$M_\chi \cdot \bar{J}(\theta)$ Inner
Plain diffusion [20]	-2.68	3.8	0.65
Diffusion reacc. [21]	-2.75	9.9	1.5

TABLE I. Angular averaged $M_\chi \cdot \bar{J}$ in central ($|\theta| < 1^\circ$) and inner ($|l| < 80^\circ, |b| < 8^\circ$) galactic regions. α_p is the power index of the proton flux. J is evaluated with reference energy E_0 at 10 GeV. See Eq. A4 for definitions. The dark matter profile is given in Eq. 14. $M_\chi \cdot J(\theta)$ values are in the unit of $10^{28} \text{s}^{-1} \text{m}^{-4} \text{sr}^{-1}$.

We choose two template Galprop CR profiles, the plain diffusion model 999726 [20] and diffusion-reacceleration model 599278 [21] to calculate the integrated strength of gamma ray source, $\int J(\theta) d\theta$ in Fermi's angular windows [22], as shown in Tab. I. For the dark matter halo we pick the Einasto profile [23] as an example for cuspy dark matter distribution,

$$\rho_\chi = \rho_\odot e^{-\frac{2}{\alpha}[(r^\alpha - r_\odot^\alpha)/r_s^\alpha]}, \quad (14)$$

where $\alpha = 1.7$, $r_\odot = 8.3$, $r_s = 25$ kpc and the local halo density $\rho_\odot = 0.3 \text{ GeV/cm}^3$.

Inside the Milky Way, however, the proton-dark matter scattering is at an disadvantage to due the relatively low level of cosmic ray flux. Small mass splitting between ϕ, χ may face increasingly stringent constraint from direct detection experiments. As Eq. 1 and Fig. 2 illustrate, only cosmic protons of $\mathcal{O}(10 - 100)$ GeV or above significantly contribute to the gamma ray signal for our toy Lagrangian. As the result the p, χ collision signal is dwarfed in comparison to the astrophysical background.

VI. SUMMARY

In this paper we investigated the gamma ray signal from the collision between dark matter and high energy cosmic ray protons, including the effects of hadronization and showering. This extends previous parton-level only calculations, with a substantial modification of the rate and energy spectrum of the photons. The rate is significantly enhanced, since the photons produced in hadronic decays have a high multiplicity and are not suppressed by the fine structure constant. In particular, we emphasize the contribution from the energetic proton remnants, which boost the high energy tail of the gamma ray spectra. To illustrate the shower enhancement to a parton level photon radiation, we implemented a simple Majorana fermion dark matter that couples right-handedly to the up-quark, to avoid large annihilation rates. We used the latest XENON100 limits to select viable test masses for the dark matter and scalar u partner for the cosmic signal from Cen A as an AGN candidate, and the case of diffuse protons in our Milky Way galaxy.

We use the Monte Carlo generator Sherpa to simulate one-sided proton remnant in a χ, p collision event and subsequent showering. Due to limited choice of generators that allow remnant showering with exotic particle beams, it is of interest to further test the photon radiation from proton remnants with alternative means of calculation. This will help to determine whether there are large theory uncertainties on this gamma ray signal. An additional source of uncertainty is the amount of AGN protons which are pointed towards the Earth. This also affects the high energy photons and thus, improvements in AGN modeling will also help pin down this part of the spectrum.

To summarize, we find that hadronization and showering substantially enhance the signal and in particular, the proton remnants significantly enhance the signal rate for the energy range $E_\gamma > M_\phi - M_\chi$, making the protons pointed directly towards the Earth the major contributor at large photon energy. The gamma ray signals from proton-dark matter collision is found to be at a level which could be potentially constrained by forthcoming Fermi measurements. In contrast, collisions with diffuse protons inside the Milky Way suffers from the low proton flux at energies high enough to reach resonance scattering. However, if the dark matter candidate and the mediator are light the signal

from diffuse protons may become more prominent.

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Appendix A: Diffuse cosmic ray scattering

The prompt photon flux at the Earth is an integral over collision sources inside the observation angular cone $\Delta\Omega$,

$$\begin{aligned} \frac{d\phi_\gamma}{dE_\gamma} &= \int \frac{dV}{4\pi r^2} \frac{dN_\gamma}{dE_\gamma dV} \\ &= \int \frac{d\mathbf{r}}{4\pi|\mathbf{r}|^2} \cdot 4\pi \int_{E_\gamma}^{+\infty} \frac{\rho_\chi(\mathbf{r})}{M_\chi} \frac{d\phi_p}{dE_p}(\mathbf{r}) \frac{d\sigma(E_p, E_\gamma)}{dE_\gamma} \end{aligned} \quad (\text{A1})$$

where $\mathbf{r} = (r, \theta)$ with θ in galactic coordinates, ρ_χ is the dark matter density and $\frac{d\phi_p}{dE_p}$ is the 4π averaged galactic proton flux.

Only the high-energy protons are relevant in our study and the spectrum can be parametrized as a power-law,

$$\frac{d\phi_p}{dE_p} = \phi_p^0(E_0) \left(\frac{E_p}{E_0} \right)^{-s} \quad \text{for } E > E_0 \quad (\text{A2})$$

where the power index s grows slightly as protons lose energy during their propagation to the outer region of the galaxy. In the Galprop models we adopted, the variation $\delta s \sim 10^{-2}$ in the power-law index is insignificant and s can be approximated as a constant.

Thus the energy integral can be separated from the spatial one and Eq. A1 can be written into

$$\frac{d\phi_\gamma}{dE_\gamma d\Omega} = J(\theta) \cdot I(E_\gamma), \quad (\text{A3})$$

$$\text{where} \quad J(\theta) = \int_0^{+\infty} dr \frac{\rho_\chi(r, \theta)}{M_\chi} \phi_p^0(E_0, r, \theta), \quad (\text{A4})$$

$$I(E_\gamma) = \int_{E_\gamma}^{+\infty} dE_p \left(\frac{E_p}{E_0} \right)^{-s} \frac{d\sigma(E_p, E_\gamma)}{dE_\gamma}. \quad (\text{A5})$$

The energy integral $I(E_\gamma)$ gives the shape of the prompt gamma ray spectrum and is independent from astrophysics. In the case with hadronic shower, the differential cross-section in Eq. A5 is replaced with

$$\frac{d\sigma(E_p, E_\gamma)}{dE_\gamma} \equiv \sigma_{tot}(E_p) \frac{d\tilde{N}_\gamma}{dE_\gamma}. \quad (\text{A6})$$

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